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Recent Advances in Vibroacoustics

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Recent Advances in Vibroacoustics

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Numerous vibroacoustics advances and impacts in the aerospace industry have occurred over the last 15 years. This article addresses some of these that developed from engineering programmatic task-work at the NASA Glenn Research Center at Lewis Field.

The understanding of vibroacoustics, the study of acoustic disturbances and the resulting structural vibration, is very critical in the aerospace industry. The high intensity acoustic fields produced during a launch of a Space Shuttle or an Expendable Launch Vehicle (ELV) can easily damage a spacecraft's mission critical flight hardware, such as its avionics, antennas, solar panels and optical instruments. This hardware may also be damaged by several flight pyroshock events. Due to this, NASA, DOD and the commercial spacecraft companies expend great effort in understanding their acoustic, random vibration and shock environments and the resulting structural response of their flight hardware to these excitations. Typically, flight hardware is dynamically test qualified to environments greater than the expected flight environment in order to ensure success. Testing occurs at various stages of hardware buildup such as at the system-, subsystem-, and component-level.

NASA Glenn Research Center (GRC) at Lewis Field has a rich history of pioneering rocket engine, space power and propulsion technology. NASA GRC was formerly known as NASA Lewis Research Center (LeRC), until its official renaming on March 1, 1999. The Center's landmark research in rocket tests with liquid hydrogen and liquid oxygen systems resulted in the successful development of the Centaur upper stage. NASA GRC soon became responsible for the management of the design, building and launch of the Atlas/Centaur and the Titan/Centaur booster vehicles. Between 1963-1998, NASA GRC managed over 100 successful unmanned launches (Figure 1). The Centaur was the upper stage for the vast majority of these launches that encompassed scientific, communications, weather and planetary exploration missions. Prominent amongst these missions were Surveyor, Pioneer, Viking, Voyager, GOES, EOS, and Cassini. On October 1, 1998, NASA GRC's role of overall management of NASA's intermediate and large ELV missions ended when this responsibility was officially transferred to NASA Kennedy Space Center (KSC).

However, NASA GRC's interest in vibroacoustics continues today in order to ensure the flight success of both its space experiments and its new power and propulsion technologies. Additionally, recent emphasis has intensified the need to analyze, understand and reduce the effects of acoustic and vibration disturbances on the microgravity environment that is so critical to the success of the microgravity science experiments on the International Space Station (ISS).

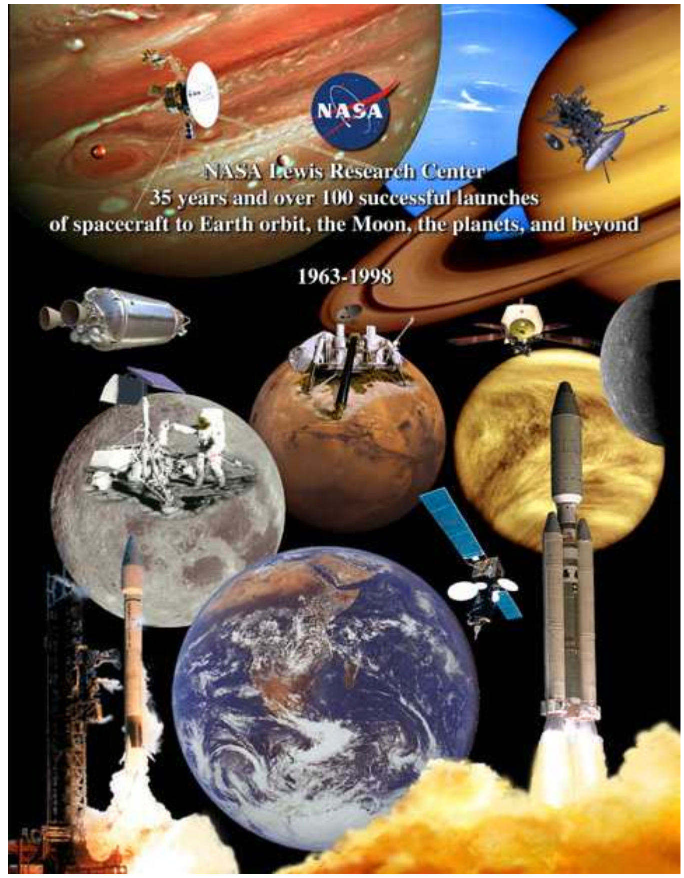

Figure 1. NASA Glenn Research Center's ELV history.

Statistical Energy Analysis

Statistical Energy Analysis (SEA) is a technique to analyze and predict the vibroacoustic response of a structure. Originally developed in the early 1960's, the usage of SEA techniques in the aerospace industry was revitalized in the late 1980's. Within the limitations imposed by SEA theory, these techniques can provide an accurate and quick vibroacoustic analysis that also easily allows for parameter redesign.

An early application of SEA at NASA GRC was the vibration prediction of a satellite's components. NASA GRC developed the Advanced Communications Technology Satellite (ACTS) in cooperation with the telecommunication industry in the late 1980's (Figure 2). Its innovations in communication was its utilization of higher frequency bands that provide higher data rates, new onboard switching to accommodate more users, and new antennas that allow the use of smaller ground based receiving dishes and wider coverage. ACTS was launched on STS-51 on September 12, 1993 and was also the first Space Shuttle use of the Transfer Orbit Stage (TOS).

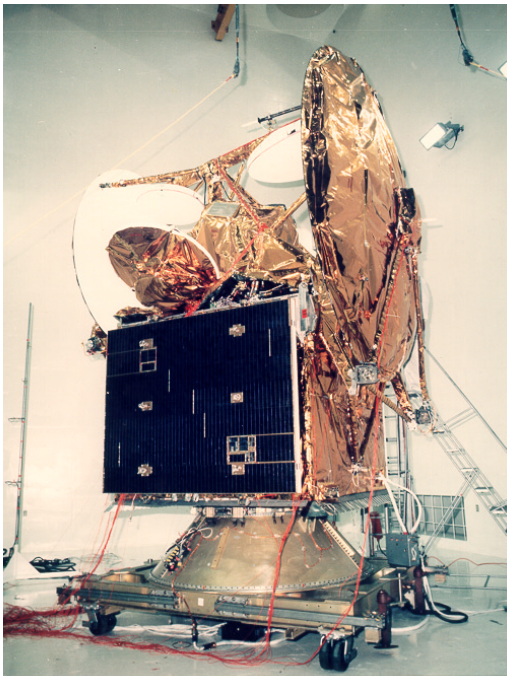

Figure 2. ACTS satellite in acoustic test configuration.

In order to predict the vibration response of the ACTS spacecraft's components when exposed to the Shuttle's acoustic excitation, a computer program called VAPEPS was utilized. VAPEPS (Vibroacoustic Payload Environment Prediction System) was originally developed at Lockheed in 1984 and distributed by the VAPEPS Management Center at the Jet Propulsion Laboratory (JPL) from 1985 until 1994. Since then commercial SEA codes such as SEAM® (Cambridge Collaborative, Inc.) and AutoSEA® (Vibroacoustic Sciences Limited) have also become popular.

The ACTS satellite, like most of today's modern spacecraft, is constructed of unreinforced honeycomb panels. Additionally these very lightweight panels are heavily loaded with relatively massive equipment such as batteries and avionics components. It was found that VAPEPS predictions for such structures were very conservative, especially at the lower frequencies. NASA GRC engineers worked with Cambridge Collaborative, Inc. to improve VAPEPS. Modifications were made to the computation of the panel's radiation efficiency, as well as to the way the non-structural mass is modeled and coupled (Reference 1). These improvements were incorporated into the VAPEPS code as "Path 49" and has since also been incorporated into AutoSEA®.

The benefits realized by using Path 49 are illustrated by the results of the ACTS analysis. A VAPEPS analysis, using Path 49, was performed to predict the vibration response of the 71 ACTS components (avionics boxes, batteries, etc.) to the simulated Shuttle acoustic excitation produced in the spacecraft level acoustic ground test. This analysis predicted that 59 of these components would respond at levels below which they had been already qualified to via component-level random vibration testing. The remaining 12 components were predicted to have spacecraft acoustic test responses that would exceed their component-level qualification vibration test response. When the actual spacecraft acoustic test was performed in March 1992 this prediction was confirmed with 99% accuracy. A total of 13 components, including all 12 that were predicted, had exceedences. Subsequently those components underwent substantial additional scrutiny and analysis to determine their suitability for flight.

NASA GRC continued to perform SEA, using VAPEPS, to analyze the vibroacoustic response for other NASA flight structures such as Space Station's photovoltaic arrays, orbital replacement units, and Solar Dynamics power concentrator. Additionally, SEA was used extensively in calculating the noise reduction of the Atlas, Commercial Titan and Titan IV payload fairings in order to define the interior acoustic environment for numerous spacecraft programs.

Acoustic Fill Factor Testing

Understanding acoustic fill effects for specifying an acoustic environment is critical for payload hardware design and testing. Fill effect is the term used to describe the changes in the interior sound levels of an expendable launch vehicle's (ELVs) payload fairing or the space shuttle's cargo bay caused by the presence of the payload. Often, the acoustic environment defined for the shuttle or an ELV represents the unfilled environment (i.e., the environment expected for an empty cargo bay or empty payload fairing). It is then necessary to account for the presence of the payload and its fill effects on increasing the empty interior acoustic environment.

Historically the fill effects on the acoustic environment were determined from one of three fill factor curves available within the aerospace community. To reduce disputes between multiple organizations involved with a NASA program while maintaining the proper acoustic environments, NASA developed a fill effects standard based on test results.

NASA Glenn, in conjunction with General Dynamics Space Systems Division (GDSSD), completed a test program to investigate the acoustic fill effects for an unblanketed payload fairing. This testing was performed in March 1994 at GDSSD's reverberant acoustic test facility in San Diego. The excellent test data obtained was used to quantify the effects of payload shape, size, and volume on the acoustic levels for four different spacecraft payloads.

Engineers at NASA GRC and Cambridge Collaborative Inc. used this test data to benchmark a statistical energy analysis methodology that can predict the fill effects for any size payload (Reference 2). This methodology has since been incorporated into the NASA standard for "Payload Vibroacoustic Test Criteria", NASA-STD-7001 (Reference 3).

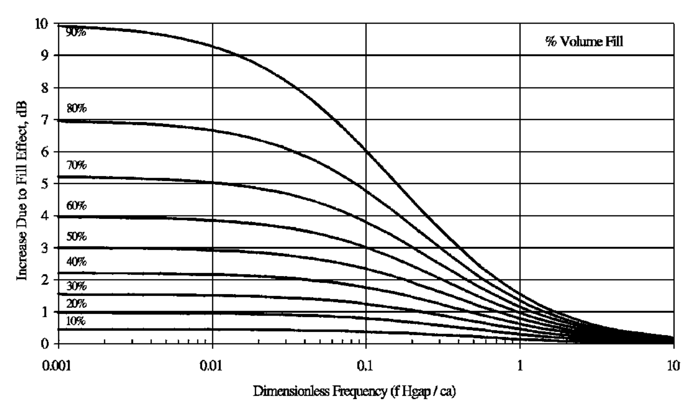

Figure 3. Fill effect design chart.

Figure 3 quantifies the fill effect's controlling parameters. The fill effect is greater (1) at lower frequencies, (2) for smaller gaps between the vehicle wall and spacecraft, and (3) for larger payload volume fill.

Blanket Development and Testing

Acoustic blankets are used in the payload fairing of expendable launch vehicles to reduce the fairing's interior acoustics and the subsequent vibration response of the spacecraft. The Cassini spacecraft (Figure 4), launched on a Titan IV/Centaur in October 1997, required acoustic levels lower than those provided by the standard Titan IV blankets. Lower interior acoustic levels were needed in order to avoid an extremely costly vibration requalification of the Cassini's spacecraft on-board electric power source known as the Radioisotope Thermoelectric Generators (RTG). Therefore, new acoustic blankets were developed and tested to reach NASA's goal of reducing the Titan IV acoustic environment to the allowable levels for the Cassini spacecraft and RTGs.

To accomplish this goal, the Cassini vibroacoustic team, consisting of members from the NASA GRC, JPL, Lockheed Martin Corporation, McDonnell Douglas Corporation, Aerospace Corporation, Analex Corporation and Cambridge Collaborative Inc., developed and performed a two-phase test program, in 1994–1995 (References 4–6). In Phase One, 19 different blanket designs were tested in a flat-panel configuration at the Riverbank Acoustical Laboratory in Geneva, Illinois. The parameters evaluated included the blanket thickness and batting density, and the placement and density of an internal barrier. Each blanket's absorption and transmission loss characteristics were quantified and the two leading designs were selected for the Phase Two test series.

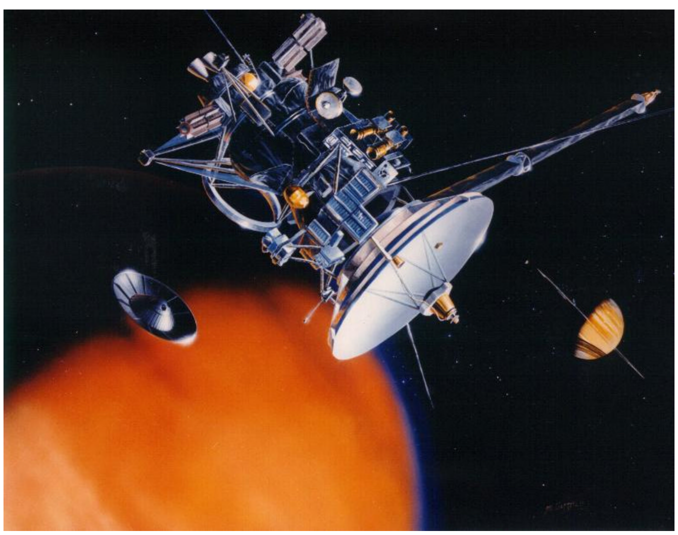

Figure 4. Rendition of Cassini spacecraft approaching Saturn.

Phase Two consisted of acoustic testing of the two new blanket designs, along with the standard Titan IV blanket design, in a flight-like, full-scale (60-ft tall) cylindrical payload fairing with a spacecraft simulator. This testing was performed at Lockheed Martin's reverberant acoustic chamber in Denver (Figures 5–7). Measurements of the acoustics and spacecraft vibration with both the new blankets and with the standard Titan IV blankets were made and compared.

Both of the new blankets designs tested in Phase Two achieved the pretest goal of significantly reducing the fairing's acoustic environment and spacecraft vibration response. The acoustic reduction achieved was 3 to 4 dB (decibels) at the 200 and 250 Hz one-third-octave band, which were the frequencies of key concern for the RTGs. Indeed, acoustic reduction was achieved over the entire frequency spectrum. One of the two new blanket designs was selected and performed successfully on the Cassini mission. Because of this successful blanket development test program, the RTG did not have to be redesigned and requalified, and an estimated $30 million in cost savings was achieved for the Cassini program.

These blankets have since been used for other Titan IV missions. In addition, a wealth of information was obtained about how acoustic blankets work and how these blankets affect the acoustics within a payload fairing.

Figure 5. View of acoustic blankets looking down into fairing.

Figure 6. Full-scale payload fairing in acoustic test chamber.

Figure 7. Simulated Cassini spacecraft atop Centaur stage.

The thoroughness involved with this ground acoustic test program combined with the presence of identical Cassini flight measurements resulted in a rare comparison (References 7–8) of flight acoustics (generated by a progressive acoustic field) with ground test acoustics (generated by a reverberant acoustic field). Additionally, unique coherence measurements of flight acoustics were also obtained during the Cassini flight.

Pyroshock Analysis

Pyrotechnic shock, or pyroshock, is the transient response of a structure to loading induced by the ignition of pyrotechnic (explosive or propellant activated) devices. These devices are typically used to separate structural systems (e.g., separate a spacecraft from a launch vehicle) and deploy appendages (e.g., solar panels). Pyroshock is characterized by high peak acceleration, high-frequency content, and short duration. Because of their high acceleration and high frequency, pyroshock can cause spaceflight hardware to fail. Verifying by test that spaceflight hardware can withstand the anticipated shock environment is considered essential to mission success.

The Earth Observing System (EOS) AM–1 (or Terra) spacecraft (Figure 8), for NASA's Mission to Planet Earth, was launched on an Atlas IIAS vehicle in December 1999. NASA GRC was the launch vehicle integrator for this NASA Goddard Space Flight Center spacecraft. The EOS spacecraft or simulator was subjected to numerous ground shock tests to verify that its scientific instruments and avionics components could withstand the shock-induced vibration produced when the spacecraft separates from the launch vehicle.

The payload separation system used for EOS was a new system that operated by firing six separation nuts. This system was tested to verify its functional operation and to characterize the resulting shock levels. The launch vehicle contractor (Lockheed Martin Astronautics) and spacecraft contractor (Lockheed Martin Missiles & Space) completed 16 separation test firings in 1997. This resulted in an unusually large amount of pyroshock data. Typically, only one or two pyroshock test firings are performed for a spacecraft mission.

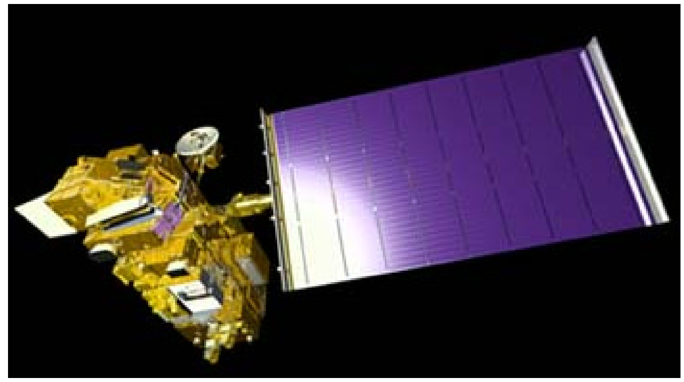

Figure 8. Rendition of EOS Terra spacecraft on orbit.

Because of the size of this separation system shock database, GRC engineers were able to perform unique statistical analyses to characterize the distribution of the test data. For example, it was proven that the shock data follow a lognormal distribution, a concept often assumed but rarely proven. The test-to-test repeatability of the shock source level was analyzed, and the effects of various test configurations (Figures 9–10) and separation nut production lots were examined and quantified.

All 16 pyroshock separation tests of the EOS spacecraft/ simulator produced its own set of six interface accelerometer data. Probability distributions, histograms, the median, and higher order moments (skew and kurtosis) were analyzed. Each set of log normally transformed test data produced was analyzed to determine if the data should be combined statistically. Statistical testing of the data's standard deviations and means (F and t testing, respectively) determined if data sets were significantly different at a 95 percent confidence level. If two data sets were found to be significantly different, these families of data were not combined for statistical purposes.

This methodology (Reference 9) produced three separate statistical families of interface shock data. For each population, a P99.1/50 (probability/confidence) per-separation nut firing level was calculated. By using the binomial distribution, GRC engineers determined that this per-nut firing level was equivalent to a P95/50 per-flight level. The overall

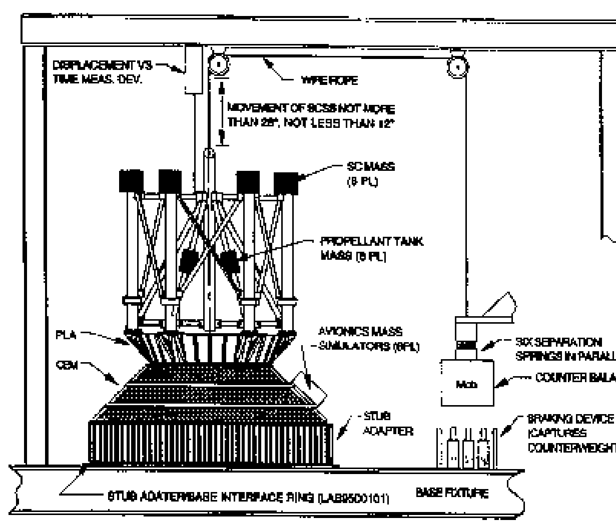

Figure 9. Lockheed Martin Astronautics test configuration.

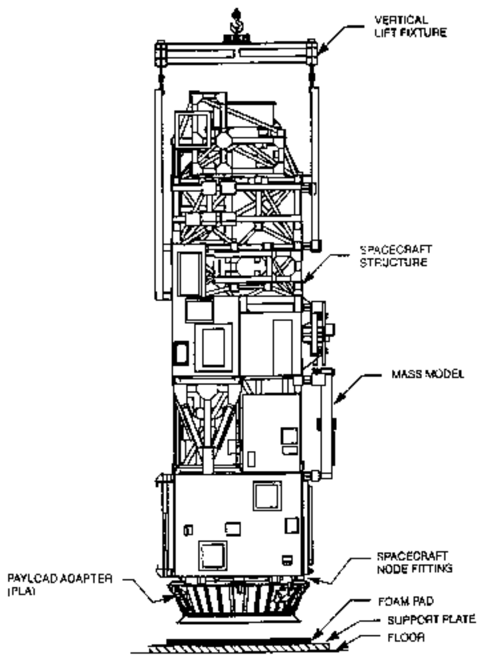

Figure 10. Lockheed Martin Missiles & Space test configuration.

envelope of these three, statistically distinct, per-flight levels led to a GRC recommended EOS interface shock specification significantly below that of the previously specified levels of Lockheed Martin derived from standard enveloping methods. This statistical analysis prevented a costly requalification of the spacecraft's instruments, which otherwise would have been exposed to much higher test levels.

GRC engineers also investigated (Reference 10) the change in shock level as the shock traveled from the spacecraft separation interface to the avionics components of the upper stage and analyzed the effects of the structural fidelity (simulator versus real) of the components and their weight on vibrational response. In addition, the shock attenuation with distance and across joints was quantified and compared with concepts originally generated in 1970 by Martin Marietta Corporation. Additionally, the effects of separation nut preload and firing sequences effects were examined.

Because of this EOS shock testing and analyses a significant amount of new information on pyroshock and its characteristics is now available to the aerospace industry.

Vibration Testing of Spacecraft Power Systems

NASA GRC, the U.S. Department of Energy (DOE), and the Stirling Technology Company (STC) are currently developing a highly efficient, long life, free piston Stirling convertor for use as an advanced spacecraft power system for future NASA missions. GRC's Thermo-Mechanical Systems Branch provides Stirling technology expertise under a Space Act Agreement with the DOE. A Stirling system can produce electric power for the very long periods of time required for NASA's Deep-Space missions to the outer planets, being four times as efficient as RTG and outlasting batteries. Stirling technology is also under consideration as the electric power source for future Mars rovers, whose mission profiles may exclude the use of photovoltaic power systems such as exploring at high Martian latitudes (reduced sunlight) or for scientific missions of lengthy durations (dust accumulation).

A Stirling power system would be the first dynamic (i.e., moving parts) power system in space, and therefore concerns on its dynamic survivability must be answered. Four structural dynamic test programs were recently performed on Stirling Technology Demonstration Convertors (TDC) to address this concern. The TDC units were designed and built by STC under contract to DOE. This testing was performed at NASA GRC's Structural Dynamics Laboratory (SDL-Reference 11) and Microgravity Emissions Laboratory (MEL-Reference 12).

The first test program, in November-December 1999, demonstrated that the Stirling TDC is able to withstand the harsh random vibration experienced during a typical spacecraft launch (Figure 11), and survive with no structural damage or functional power performance degradation (References 13–14). This was a critical step in enabling the usage of Stirling convertors for future spacecraft power systems. The random vibration test levels between 20 and 2,000 Hz were chosen by the Jet Propulsion Laboratory to simulate, with margin, the maximum anticipated launch vibration conditions.

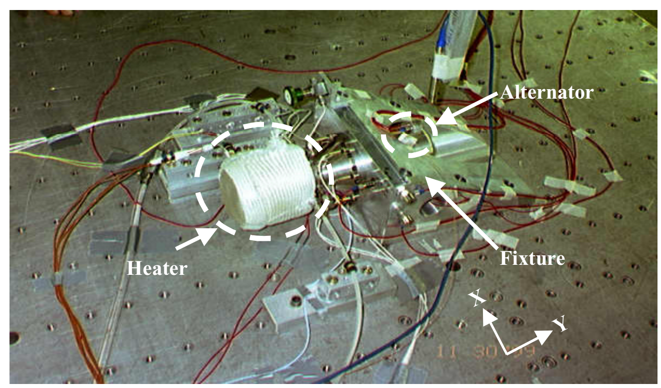

Figure 11. Vibration testing of Stirling TDC.

A single 55 electric watt TDC was operated at full-stroke and full power conditions during this vibration testing. It was tested in two orientations, with the direction of vibration parallel and perpendicular to the TDC's moving components (displacer and piston). The TDC successfully passed a series of sine and random vibration tests. The most severe test was a 12.3 grms random vibration test (peak vibration level of 0.2 g2/Hz from 50 to 250 Hz) with test durations of 3 min per axis.

The Microgravity Emissions Laboratory (MEL) facility at GRC is typically utilized to measure the dynamics produced by operating Space Experiments and the resulting impact to the International Space Station's microgravity environment. For the second Stirling test program, performed in January 2001, the MEL was used to characterize the structure-borne disturbances produced by the normal operation of a pair of Stirling convertors (Figure 12).

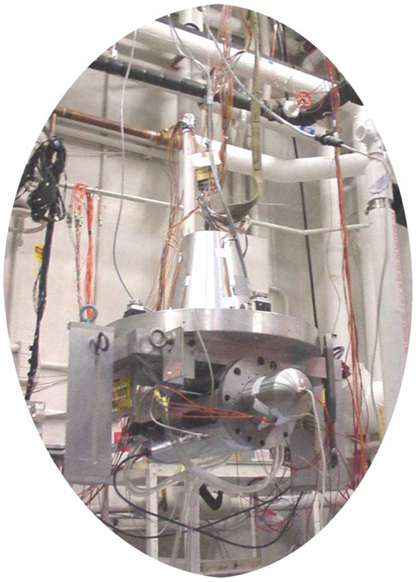

Figure 12. Vibratory emissions testing of a Stirling TDC pair.

The forces and moments produced by the normal operation of a Stirling system must be recognized and controlled, if necessary, in order that other nearby spacecraft components, such as cameras, are not adversely affected. During testing the Stirling convertor pair emitted relatively benign tonal forces at its operational frequency and associated harmonics. Therefore, Stirling systems should be a non-disturber to spacecraft science provided that minimal appropriate mounting efforts are made.

The third Stirling dynamic test program, performed in February and May 2001, resulted in a modal characterization of a Stirling convertor (Reference 15). Since the deflection of the TDC piston rod, under vibration excitation, was of particular interest the outer pressure shell was removed to allow access to the rod. Understanding the system's natural frequencies and how these might align with the launch excitation frequencies will result in improved dynamic capability and potentially increased power performance for future Stirling designs.

The fourth test program, in May 2001, was conducted to characterize the structural response of a pair of Stirling convertors, with various mounting interface stiffness (Reference 16). The resulting vibration transmissibility measurements will aid future system integrators in developing the structural interface between the spacecraft and the Stirling power system, and also the interface between a pair of convertors.

Dynamic testing performed to date at NASA GRC has shown that the Stirling convertors are capable of withstanding liftoff random vibration environments and of meeting "good neighbor" vibratory emission requirements. Furthermore, dynamic test data has been obtained which will allow the Stirling system integrator to optimize their convertor and system interfaces design.

Combined Environmental/Modal Rack Testing

NASA GRC's Structural Dynamics Laboratory (SDL) has a 15-year history of vibration qualifying combustion and fluid microgravity science hardware for missions on the Shuttle and the International Space Station. This hardware includes vibration sensitive optics, critical alignment devices, and commercial-off-the-shelf (COTS) electronics that are not designed to withstand the harsh liftoff vibration environment of the Shuttle.

Traditional aerospace vibration testing of flight hardware includes environmental vibration qualification and modal test characterization. These tests are typically performed separately. In 1999, combined environmental/modal vibration testing was implemented in at the NASA GRC SDL. The benefits of combined vibration testing are that it facilitates test article environmental vibration testing and modal characterization.

The Combustion Module–2 (CM–2) is a combustion science experiment consisting of eight packages integrated into SPACEHAB single and double racks. CM–2 is manifest to launch on Shuttle mission STS–107 in the SPACEHAB Research Double Module. The CM–2 hardware is a re-flight of CM–1 hardware, which was originally designed and environmentally qualified for Spacelab and flew on Shuttle missions STS–83 (April 4, 1997) and STS–94 (July 1, 1997). The CM–2 design loads and vibration environments for SPACEHAB are higher than CM–1, requiring re-qualification of the CM–2 hardware for mission assurance.

CM–2 rack level combined vibration testing was completed on a shaker table to characterize the structure's random vibration and modal response (Figure 13, Reference 17). Control accelerometers and limit force gauges, located between the fixture and rack interface, were used to verify the input excitation. Results of the testing were used to validate the loads and environments for flight on the Shuttle.

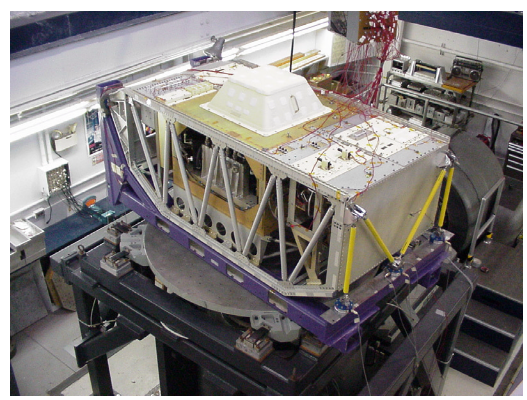

Figure 13. CM–2 double rack vibration testing.

The application of combined environmental/modal testing for the CM–2 flight program was a cost effective way to reduce the design load factors and verify the package environments for mission assurance. The advantage of rack level testing is it provides flight boundary conditions to the package. Performing rack level testing instead of individual package level tests saved the program one-half the testing time. Integrated rack level testing provided mass attenuation reducing the package interface random vibration response. The rack test excitation was controlled to ¼ of flight excitation levels. This reduced the fatigue exposure to the CM–2 commercial, vibration sensitive electronic hardware. Package vibration responses from the rack level testing were scaled to flight excitation levels and compared with previous CM–1 package qualification testing. By reducing the CM–2 package loads and vibration environments, the CM–2 program saved the cost of hardware re-qualification and redesign.

Microgravity Disturbance Characterization

In order to preserve the microgravity environment on the International Space Station (ISS), vibration emissions from science experiments need to satisfy on-orbit microgravity vibration requirements. The Fluids and Combustion Facility (FCF), a NASA GRC microgravity facility dedicated to combustion and fluids science, will have permanent presence on the International Space Station.

In January 2002, empty ground rack testing (Figure 14) was conducted in NASA GRC's Acoustical Testing Laboratory (ATL-Reference 18) anechoic acoustic chamber as an initial step in characterizing the vibration emission from an operating fan within the FCF rack. The fan excitation source is recognized as a significant microgravity vibration disturber, and produces both acoustic (air-borne) and mechanical (structure-borne) excitation.

The test configuration included an empty aluminum ground rack designed by Boeing for the International Space Station. The rack was instrumented with 43 response accelerometers distributed across the rack panels and posts. Five microphones were mounted internal to the rack cavity to quantify the rack internal acoustic excitation levels. A mechanical shaker, mounted to the rack post, was used to simulate fan forces emitted due to impeller imbalance. The actual fan forces were measured in NASA GRC's Microgravity Emissions Laboratory (MEL). A 12-inch speaker, mounted at the bottom of the rack, was used to simulate the fan acoustic excitation. The actual fan acoustic excitation was measured at a 2-foot distance from the fan's surface in NASA GRC's ATL. The fan acoustic (speaker) and mechanical force (shaker) excitation were produced using a pink noise signal generator and spectrally shaped with a one-third-octave band equalizer.

Figure 14. FCF ground rack disturbance testing.

The effect of structural-acoustic coupling (Figure 15) on the rack vibration response is an important interaction that influences the microgravity environment. Simulating the fans acoustic (air-borne) and mechanical (structure-borne) excitation allows for the characterization of the relative vibration contribution from each source. Results from this empty ground rack testing and future tests with racks populated with experiment hardware will be used to assess the impact of FCF components on FCF science and ISS microgravity requirements.

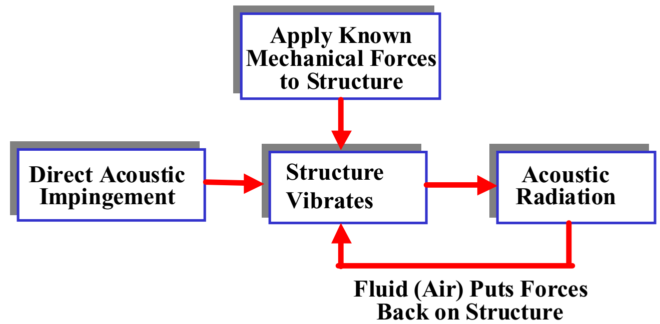

Figure 15. Structural-acoustic coupling.

Summary

As illustrated in the cases discussed in this article, the world of vibroacoustics is diverse, interesting and challenging. These cases are just a sample of the many advances, in testing and analysis, which have been made over the last 15 years throughout the aerospace industry. It is our hope that the readers will continue to advance the technical understanding of acoustics, random vibration and pyroshock and successfully apply their new knowledge to the next generation of spaceflight hardware design, test and analysis.

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Numerous vibroacoustics advances and impacts in the aerospace industry have occurred over the last 15 years. This article addresses some of these that developed from engineering programmatic task-work at the NASA Glenn Research Center at Lewis Field.

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